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Enhanced Southern Ocean marine productivity due to fertilization by giant icebergs

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Methods

The giant iceberg tracks used for the main analysis come from the Brigham Young University Center for Remote Sensing Iceberg Tracking database (www.scp.byu.edu/data/iceberg/database1.html) which uses satellite scatterometer backscatter to identify giant icebergs[26]. The resolution achievable by these satellite sensors is 4-5 km[26], but only those icebergs meeting the giant iceberg definition of having an L_i > 18 km enter the database from which we selected the icebergs to be analysed. All icebergs examined are therefore well resolved.

Once the positions of giant icebergs were obtained, the Level 1 and 2 MODIS ocean colour images were exported from oceancolor.gsfc.nasa.gov using SeaDAS software v7.0.2. Chlorophyll concentrations were analysed from eleven years (2003-2013) for 65 positions during a one-month period 20 days prior to a giant iceberg passage, 63 positions for the seven-day period post-passage, and 47 values for the seven-day period following the iceberg passage. These came from 17 giant iceberg tracks (see Supplementary Table S1). The number of positions for icebergs from the A-D sectors were 22, 16, 15 and 10 respectively. The positions were taken from sea-ice free areas, restricting the number of possible images analysed from sectors B-D, and were almost all from equatorward of 60^{o}S. Only portions of tracks were chosen where it was clear that the icebergs were not grounded, as can be seen from the sequence of positions in Supplementary Table S1. Note also that the one iceberg, C19a, which was followed both before and after austral winter (2008) remained in

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open water throughout the entire time between its first and last used image[27].The mean chlorophyll concentration was obtained from a 15 km radius centred on the iceberg's geographical coordinates using the geometry mask tool from the SeaDAS software. The significant time difference between the before and after passage values was used because of the presence of major plumes both upstream and downstream from a giant iceberg's position (Figure 1).

A selection of 20 images (Supplementary Table S2) where a clear and delimited plume of increased chlorophyll could be visually associated with the iceberg was chosen to draw a chlorophyll concentration profile with respect to distance from the iceberg (Figure 2b). These images were selected according to the following four criteria.

1. Minimizing the degree of cloudiness around the iceberg and its surrounding sea water. From all NASA Ocean Colour images examined on a daily basis during the austral summer periods of 2003-2013, only a few dozen were sufficiently clear of clouds for it to be possible to identify the location of the iceberg and visualise the extent of its surrounding plume as a whole.

2. Clarity of the border of the plume. From the selection above, we chose the images with the clearest contrast between the iceberg's plume colour and the surrounding sea water. Highly dissipated or scattered plumes were rejected due to the uncertainty of the link to the iceberg.

3. Maximising the distance from shorelines and seasonal icepack. The images were all selected in the summer period and were far away from the seasonal icepack around the Antarctic continent. Images where the icebergs were close to South Georgia (a common route for giant icebergs coming out of the Weddell Gyre) were

not employed so as to avoid any interference from sedimentary iron released from the island's shelf.

4. Ensuring that icebergs were free-drifting. All the 20 images used were taken from part of the free drifting routes of the icebergs concerned. This was easily verified from the daily changing position of the icebergs during the previous and following days of the selected image.

From the images selected, a line was drawn from the iceberg edge toward the background value traversing the plume along its longest axis. Along this line, chlorophyll concentrations were obtained from 0, 3, 5, 10, 20, 40, 60, 80, 100, 200, 400, 600, 800, 1000 km distance from the iceberg and Figure 2b was generated from the mean value and standard deviation of observations from each distance.

There are clear limitations to the study. The number of images obtained were restricted due to the high degree of cloudiness of the Southern Ocean, and the limited number of sun-lit months further south. A number of the images are likely to be affected by other iron sources, such as coastal sediment fluxes from South Georgia[28, 29], although this was minimized as much as possible. Another limitation is that MODIS tends to overestimate chlorophyll concentrations that are low, minimizing the impact found. However, overall, MODIS's error accuracy for surface layer measurements in depths > 20 m is close to the instrument 35% target error[30]. A final limitation is that deep chlorophyll concentrations may occasionally be disturbed by passage of an iceberg, leading to an artificially enhanced chlorophyll level[2].

To estimate the additional carbon export through the increased area of influence of giant icebergs found in this study the following calculations were made. The observed 2.5 mg m^{-2} day^{-1} background export[18] was assumed to relate to the far-

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field chlorophyll concentration of Figure 2b. From Figure 2, this was assumed to be increased to 25 mg m^{-2} day^{-1} over an area of $\pi(4L_I)^2$, or 12.5 mg m^{-2} day^{-1} over an area of $\pi(10L_I)^2$ where a typical giant iceberg L_I ~ 30 km, and there are typical 30 such icebergs in the Southern Ocean[15, 26]. This gives a total giant iceberg export of 0.012-0.040 Gt yr^{-1}.

The images from Figure 3 were obtained from analyses and visualizations produced with the Giovanni online data system, developed and maintained by NASA GES DISC (gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=ocean_month). The track of iceberg B31 in Figure 3 comes from using a range of sources over January-March 2014: Terra and Aqua satellite MODIS reflectance, available from earthdata.nasa.gov/labs/worldview ; and SAR data from the TerraSAR-X and Radarsat2 satellites. Data on the track and evolving dimensions of B31 extending over a much longer period will be available towards the end of 2016 in the British Antarctic Survey's Polar Data Centre (https://www.bas.ac.uk/team/business-teams/information-services/polar-data-centre/).

References specific to Methods

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